WHITE PAPER TO THE NRC DECADAL SURVEY
OUTER PLANETS SUB-PANEL

Thermal Protection System Technologies for Enabling Future Outer Planet Missions

by

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INTRODUCTION

This NRC Decadal Survey white paper is a general assessment of the current availability of Thermal Protection Systems (TPS) enabling future *in-situ* exploration of the Outer Planet atmospheres. It begins with a synopsis of TPS development and its relevance for probe science conducted in the atmospheres of Saturn, Neptune and Jupiter. This is followed by a discussion of current TPS capability and issues, and concludes with recommendations for a technology program that includes TPS research, development, testing, and manufacturing capabilities required for new Outer Planet probe missions.

BACKGROUND: Historical Overview of TPS Development

For vehicles undergoing hypervelocity atmospheric flight, TPS is a single-point-failure system essential for shielding their structures and payloads from entry heating. For the Outer Planet Science community, TPS is enabling to obtain "ground truth" data by the deployment of atmospheric probes [1]. Minimizing the weight and cost of TPS while ensuring the integrity of the vehicle is a continuing challenge for the TPS community.

The development of modern TPS traces to the military's need to deliver nuclear weapons and NASA's need to return astronauts from the moon. Viable entry probes are enabled by four innovations from that era: 1) H. Julian Allen's blunt body concept, where much of the vehicle's aeroheating is blocked by a thick boundary layer associated with the bow shock wave, 2) ablative TPS, which simultaneously rejects in-depth heating by converting TPS material into gaseous ablation products that transpire into the boundary layer, forming a dark char layer which radiates heat from the vehicle's surface into the cold free stream and using the remaining virgin material as a thermal insulator, 3) arc jets to simulate TPS materials' response to aeroheating and other ground facilities used to simulate entry environments and 4) analytical models and codes that predict the aeroheating environment during entry and the thermal and ablation response of TPS materials. Two prominent ablatives from this era were Avcoat, used on the Apollo vehicle, and Carbon Phenolic (CP), used primarily by the Department of Defense (DoD).

By the late 1970s, development of ablative TPS significantly declined as the DoD's developments were completed and the Apollo program ended. NASA shifted its focus to the Space Shuttle, designed to be a reusable system, including its TPS. While *reusable* TPS development occurred in the late 1970s and through the 1980s, the *ablative* TPS community was not revitalized after the Shuttle's development. However, NASA continued to require ablative TPS for robotic entry probe missions, and used the DoD's **FM5055 CP** for the forebody heat shields of the Galileo and Pioneer-Venus probes.

The Galileo probe entered the Jovian atmosphere in 1995, prograde, near the equator at 47.4 km/s surviving the most hostile entry yet attempted. The forebody heat shield was made from two versions of FM5055 CP. The nose was made of Chopped Molded Carbon Phenolic (CMCP), while the conical flank was made of Tape Wrapped Carbon Phenolic (TWCP). Backshell heating rates are typically 2 to 10 percent of those on the forebody stagnation point. Galileo flew with a backshell TPS made of a mid-high density nylon phenolic composite ablative, no longer in production or in use for heat shields. During development of the Galileo probe, NASA Ames operated a high power arc jet facility called the Giant Planet Facility (GPF) to test in H_2/He mixtures at very high convective

heat fluxes. At this time, Ames was also operating a high-power gas dynamic laser to investigate mechanical erosion (spallation) of carbon phenolic under severe heating that obviates the ablator function described above. Fortunately, the project team had the foresight and funding to install ablation sensors in Galileo's forebody heatshield. Prior to entry, the CP nose thickness was 14.6 cm while that on the flank was 5.4 cm. After probe entry, 10 cm of CP remained on the nose, but only **one** cm remained on the conical flank. Galileo's forebody heat shield almost experienced burn through.

In 2005, NASA commissioned the Orion TPS Advanced Development Project (ADP) to rebuild its ablative program and re-establish industrial capability to manufacture Orion's forebody heat shield. ADP screening of candidate materials eliminated Shuttle tiles and SLA-561V for Space Station return, and 4 of 5 ablators for Lunar return. Only a tiled Phenolic Impregnated Carbon Ablator (PICA) architecture survived. Initially, Avcoat was eliminated because of poor performance in arc jet testing, despite the availability of the Apollo-era specification. After much effort in re-developing Avcoat's manufacturing process and maturing the tiled PICA option, the ADP and industry produced two viable PDR-level designs for Orion's forebody TPS. Avcoat was selected in April 2009 because it had fewer apparent issues in taking the heat shield design to CDR and flight.

Low-density ablators SLA-561V (originally developed for Viking) and Silicone Impregnated Reusable Ceramic Ablator (SIRCA) have been used on recent Mars missions. PICA, another low-density material invented in the mid-90's, enabled the Stardust sample return mission. In 2008, thermal issues arose in post-CDR testing of SLA-561V on the Mars Science Laboratory, and a crash effort was required to replace its heat shield with PICA.

Three things can be learned from this recent experience: 1) an "off the shelf" ablative can take several years to become viable, 2) the "workhorse" TPS that performed well on past missions may not work on the next one, and 3) had the ADP not been commissioned, the agency/industrial capability to redesign MSL's TPS in 2008 would have been lacking.

CURRENT CAPABILITY: TPS for Outer Planet Missions

While NASA has made good progress in revitalizing ablative TPS capabilities for Orion, **this TPS technology readiness assessment has identified significant gaps for the Outer Planet probe missions that require immediate attention.**

Ablative Materials

Ablative TPS are required for Saturn, Neptune and Jupiter atmospheric probes. Table 1 shows potential TPS capabilities in terms of heating rates and surface pressures for ablatives that have flown, or are at a mid technology readiness level (TRL). Table 2 lists representative stagnation point conditions for flight in Outer Planet atmospheres. It should be noted that other system-level engineering decisions, such as designing aeroshell shapes and weights, orbits and trajectories, entry speeds and angles, as well as vehicle system optimization would affect the actual entry heating conditions for each mission.

Direct entry from a hyperbolic trajectory, like Galileo's, produces the highest forebody heating rates and pressures. Aerocapture, which uses aerodynamic drag rather than retro-propulsion for orbital insertion, produces lower forebody heating rates and pressures, but significantly larger heat loads.

By comparing the potential ablator capabilities in Table 1 to representative outer planet entry conditions shown in Table 2, it is apparent that **"heritage"** carbon phenolic (HCP) is the only candidate with demonstrated capability to reliably handle the extremely high heating rates anticipated for direct entry. No materials are capable of high latitude Jovian entry. Several firms currently manufacture TWCP, but these materials cannot be considered as **"heritage"** for TPS applications because they are ***not*** made from the legacy rayon precursor and do ***not*** follow the heritage manufacturing process.

Table 1. Candidate ablative TPS materials for Outer Planet probe applications

Density	TPS	Supplier	Flight Qual or TRL	Potential Limit		Mission Set				
				Heat flux, W/cm²	Pressure, atm	Saturn Pro-grade	Saturn Retro-grade	Neptune Direct	Neptune Aerocapture	Jupiter High Latitude (Pro-grade)
FOREBODY HEAT SHIELD										
Low-Mid	PICA	FMI	Stardust	~ 1200	< 1	✖	✖	✖	✖	✖
	Avcoat	Textron	Apollo	~ 1000	~ 1	✖	✖	✖	✖	✖
Mid	ACC	LMA/ C-Cat	Genesis	> 2000	> 1	◡	✖	✖	✖	✖
	Mid-density carbon phenolic (0.8-1.0 g/cm³)	Several capable, none active	TRL 3	> 2000 < 5000	> 1	◡	✖	✖	✖	✖
	PhenCarb family	ARA	TRL 5-6	> 2000 < 5000	> 1	◡	✖	✖	✖	✖
High	3D Woven QP	Textron	DOD TRL 3	≥ 5000	> 1	◡	✖	✖	✖	✖
	Heritage Carbon Phenolic (TWCP & CMCP)	Several capable, none active	Venus, Jupiter	10,000-30,000	>> 1	●	●	●	●	✖
BACKSHELL TPS										
Low-Mid	PICA	FMI	Stardust	~ 1200	< 1	●	✖	◡	◡	✖
	Avcoat	Textron	Apollo	~ 1000	~ 1	●	✖	◡	◡	✖
	SLA-561V	LMA	Mars	~ 300*	< 1	◡	✖	✖	✖	✖
	SRAM family	ARA	TRL 5-6	~ 300*	~ 1	◡	✖	✖	✖	✖
	PhenCarb family	ARA	TRL 5-6	> 2000 < 5000	> 1	◡	◡	◡	◡	◡
	SIRCA†	Ames	Mars	< 150	< 1	✖	✖	✖	✖	✖
	Acusil® II†	ITT	DOD	< 100	< 1	✖	✖	✖	✖	✖
High	Teflon (PTFE)†	Several	Various	> 500	> 1	●	✖	●	●	✖
	AD3DQ†	Textron	DOD	< 2500	> 1	●	✖	✖	✖	✖

● Fully capable ◡ Potentially capable (qual needed) ■ Capable but heavy ✖ Not capable

*For low shear environments †RF transparent

Recalling that backshell environments are 2 to 10 percent of those for the stagnation regions shown in Table 2, it is clear that many materials listed in Table 1 are candidates for backshell TPS for future Outer Planet probes. Several are RF transparent, enabling communications. For the Jupiter higher latitude and Saturn retrograde missions, the backshell environments are too severe for any of the low-mid density materials.

Ground Test Facilities

A mainstay of TPS development for the past several decades has been the arc jet facilities at NASA ARC, JSC, Arnold Engineering and Development Center (AEDC) and Boeing. These high power facilities (10 to 60-MW), provide the capability for testing the largest article or highest heating range currently possible and are indispensable for TPS development and certification of flight hardware. After Galileo, with no near-term

outer planet mission in sight, the Giant Planet Facility (GPF) that operated with H_2/He mixtures and capable of extremely high convective heat fluxes, was decommissioned.

Table 2. Unblocked* stagnation point environments for potential outer planet missions

Stagnation Point Conditions	Mission Set				
	Saturn Prograde	Saturn Retrograde	Neptune Direct	Neptune Aerocapture	Jupiter Prograde
V_e (km/s)	26.8	46.4	~ 29	~ 29	47.4
$\dot{q}_{convective}$ (W/cm^2)	~ 3,000	~ 15,000	8,000	6,600-7,400	21000
$\dot{q}_{radiative}$ (W/cm^2)	~ 0	~5,000	4,000	3,800-7,400	40000
$\dot{q}_{combined}$ (W/cm^2)	~ 3000	~20,000	12,000	10,400-14,800	61000
$p_{stagnation}$ (atm)	1.4	10	< 5	< 1	9.5
Relevant arc jet test	Yes	No	No	No	No

*Assumes all convective and radiation heating reaches the TPS. Blockage significantly reduces the effective heating rate. For Galileo, the effective heating rate was ~17 kW/cm^2 [2].

While existing arc jet facilities **are not capable** of simulating the high combined heat flux associated with almost all of the outer planet missions, TPS materials can be tested with high-energy lasers to estimate the level of heat flux required to initiate char spallation, discussed above. LHMEL II at the Wright Patterson Air Force Base, can produce a maximum heating of ~7,000 W/cm^2 on a reasonable size test article of 4.3 cm diameter.

ISSUES & CHALLENGES

Ablative Materials

Heritage carbon phenolic (HCP) has the demonstrated capability to handle heat fluxes in the range from 1-5 kW/cm^2 at pressures in the range from 1-10 atmospheres. Use of the heritage process and materials for both the TWCP and CMCP, including the legacy precursor rayon, would allow the finished materials to be considered "heritage". The **current** TWCP is **not** made from legacy precursor rayon and processes and **cannot guarantee** the performance and reliability levels of heritage CP established by the extensive ground and flight database provided by the DoD and Galileo's flight certification. While several vendors manufacture TWCP, CMCP has rarely been made since the Galileo program.

Today's supply of the specific rayon precursor used to fabricate the heritage carbon phenolic is extremely limited. The U.S. companies with the capability to fabricate rayon suitable for heat shield development have gone out of business. NASA Ames acquired a modest supply of 1970s vintage rayon from the limited stockpile held by the Navy's Strategic Systems Program Office, enabling the Agency to fabricate a only few heritage CP heat shields of modest size for upcoming space missions requiring a high performance heat shield.

Another significant gap in materials development for entry technology is the need for mid-density ablative TPS. Whereas CP is a high-density ablative, most of the other available materials are low density. There are outer planet missions and regions on the vehicles where a mid-density ablative TPS would be the best choice. Heating rate /

pressures may be beyond the capabilities of low-density TPS materials and the use of high-density materials would impose a significant weight penalty. New ablatives in the mid-high density range offer significant mass savings for the TPS. For example, a study of Neptune Aerocapture [3] for a mid-L/D vehicle (ellipsed) entering the atmosphere at 29 km/s indicated that stagnation point heat fluxes were in the range 10-15 kW/cm^2 and heat loads > 1 MJ/cm^2. HCP could be used for the entire vehicle, but it would be heavy. Mid-density CP could not handle the conditions near the stagnation point. However, farther back on the vehicle windside, the peak fluxes are in the range 3000-6000 W/cm^2 and the mid-density CP (e.g., 0.96 g/cm^3) was estimated to perform well. Use of this material yields a mass savings of 25-40 percent (210 kg) compared to an entire TPS made of fully dense carbon phenolic (1.4 g/cm^3). **This "saved" mass trades directly with increased science payload.**

Technical Engineering Development

Current ablative TPS designers still use methodologies and tools for thermal response models developed in the 60's and 70's.

One of the major problems has been the impossibility of validating the models with flight data due to the fact that TPS instrumentation on entry vehicles generally has not been used since Apollo. Data acquired from Galileo was the exception, because ablation recession sensors were incorporated in the forebody TPS. However, the severity and uncertainty in the heating environment made interpretation of those data very difficult. Consequently, to minimize risk, TPS designs are necessarily conservative (heavy).

A final area where improved understanding could result in TPS mass savings and reduce mission risk is that of developing models that tightly couple the aerothermal environment and TPS response analysis. However, the lack of fundamental data, albeit difficult to interpret and acquire, remains an obstacle to validating these models.

Ground Test Facilities

It is impossible to simulate in a ground facility all environmental parameters (heating rate, enthalpy, pressure, shear and scale) simultaneously. Arc jet facilities continue to provide the best simulation of the TPS flight environment, with certain limitations. Importantly, the maximum heating on a reasonable size test model in current arc jets is limited to about 2.5 kW/cm^2, far short of the peak heat rates involving outer planet missions.

Although the outer planet atmospheres are primarily H_2/He mixtures, none of the existing arc jet facilities can operate with such gases. This is a serious gap given the need to obtain material performance data with correct hot gas/ablator thermochemistry. In contrast to the large production test facilities only capable of testing in air or nitrogen, a new facility - the Development Arc jet Facility (DAF) - could operate up to a maximum of 5-MW with H_2/He mixtures. Nearly all of the components required to assemble the DAF are in place, but assembly has been delayed due to a lack of funding and mission drivers. The DAF's arc heater could be configured with a "supersonic-anode" that produces very high stream-centerline enthalpy and thus heating rates appropriate for lower end outer planet missions such as Saturn. While the samples are small, ~ 2.5 cm in diameter, the tests would be meaningful because they encompass much more than a "unit cell" of carbon phenolic.

Limitations of the current TPS material test facilities dictate an alternate strategy for certain planetary missions. Qualification of TPS for potential outer planet missions will require a “piecewise approach” [4], where a laser facility could attain the complete range of predicted heating rates to understand in-depth heating profiles while the small DAF facility could provide understanding of the said thermochemistry. The existing, large arc jet facilities will continue to be important in development and qualification of TPS.

If a new probe mission to Jupiter is to be undertaken, a capability similar to or greater than that of the GPF will be required, depending upon the latitude for the entry.

RECOMMENDATIONS

TPS Materials and Heat Shield Manufacturing: Once given mission go-ahead, two typically sized heritage carbon phenolic (HCP) heat shields for Outer Planet probes could be manufactured from the legacy rayon precursor in NASA’s possession within a short period of time. It is recommended that work be undertaken to re-establish industrial capability to manufacture heritage carbon phenolic heat shields for entry probe missions using the Galileo legacy rayon and the heritage manufacturing process. This would represent the least expensive option, and could possibly be accomplished within two years. Work should be performed to qualify CP made from **other available** aerospace grade rayon precursors and heritage processing methodology. Once proven as a replacement precursor, a large stockpile of the new rayon should be acquired for the manufacture of heat shields for future explorations of both the Outer Planets and Venus as well as for the Mars Sample Return missions discussed in companion white papers. Research and development on mid-density ablatives should be undertaken, accounting for new additives, e.g., silicon carbide microballons, to lower TPS density while keeping high thermal performance.

Facilities: Because the Saturn pro-grade entry environment is less severe, establishing credible TPS capability for that mission will be the least expensive and time consuming, and could be accomplished with existing facilities and activation of the Development Arc Facility (DAF). TPS for Jupiter will require considerably more time and funding because it requires a new test facility similar to the Giant Planet Facility (GPF). Entry conditions for Neptune are intermediate, and the effort required depends on the severity of the entry mission selected. If the science interest is to go to mid-latitude Jupiter missions, given the performance limit of carbon phenolic, higher performance materials or system approaches will need to be developed, and a new ground test capability beyond that of the GPF will need to be built – making this the most expensive and time consuming of all current Outer Planet options.

Aerothermal and Materials Response Modeling, and Flight Instrumentation: Current capability in predicting ablator recession in stagnation and shear flow regions is inadequate especially for Neptune and Jupiter. If Galileo had not been instrumented with recession sensors, technologists would not know the shortcomings of their design tools for Outer Planet missions. This gap must be closed before a new Outer Planet probe is designed, and new entry probes should carry TPS instrumentation.

Specifically, it is recommended that NASA establish a cross-cutting TPS Technology program with elements focused on sustaining current technologies and others focused on

enabling both near and longer term Outer Planet Probe Missions. This program will need to focus on:

1. Re-certifying industry's capability to manufacture heritage carbon phenolic every few years until an alternate material can be qualified.
2. Developing an alternate to heritage carbon phenolic using currently available rayon and stockpile the new precursor.
3. In parallel to recommendation (2), developing new mid-to-high density TPS materials.
4. Investigating materials or systems capable of higher latitude Jovian entry if science demands such missions.
5. Ensuring that the agency retains its engineering capability in ablative TPS, improving design and analysis tools and validating them against ground and flight data.
6. Ensuring all Outer Planet Missions incorporate flight TPS instrumentation.

In conclusion, TPS development for Outer Planet Missions is a challenging, cross-cutting technology that requires specialized resources in terms of NASA's revitalized ablator expertise now available, and the above recommendations. These can be deployed to support various NASA missions. The Decadal committee should consider not only specific recommendations given here for the Outer Planets sub-panel, but also the TPS needs for other science destinations addressed in companion TPS white papers and the needs of other NASA stakeholders, including the taxpayers.

Finally, it is requested that during the course of the development of recommendations by the new decadal planning team, the TPS community be given feedback on those missions that appear to be emerging as high priority and that involve atmospheric flight. With this information, these recommendations could be focused and made more specific to a given destination. If helpful, estimates for cost and schedule could be provided upon request.

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